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APPLICATION OF ELECTRONIC FLOW ROUTING ANALOG

By Max A. Kohler, A. M. ASCE

HYDRAULICS DIVISION

Headquarters of the Society
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PAPERS

APPLICATION OF ELECTRONIC FLOW ROUTING ANALOG

By Max A. Kohler,[1] A. M. ASCE

Synopsis

Late in 1948, the Weather Bureau, United States Department of Commerce, developed an electronic device for stream-flow routing[2,3] that has proved to be highly effective in the preparation of river stage forecasts. Although originally designed for routing flows from point to point along a stream, subsequent studies indicate that the equipment is equally applicable to the direct routing of effective rainfall (runoff) over relatively large basins. This application of the flow analog and the conditions under which the original circuit fails to provide a satisfactory reproduction of the outflow hydrograph are discussed in this paper. The basis for the circuit employed in the analog and the method of operating the equipment are also discussed briefly.

Introduction

Basis of the Analog.—Stream-flow routing is usually accomplished through the simultaneous solution of two equations—one equation relating storage to the instantaneous flow in the reach and the other an equation of continuity. In the Muskingum method[4] of routing, storage is assumed to be directly proportional to a weighted value of the flow within the reach, that is,

$$S = K[x\,I + (1 - x)\,O] \qquad (1)$$

in which S is the storage; I is the inflow; O is the outflow; and K and x are constants for the reach. It can be shown that the circuit of Fig. 1(a) satisfies

Note.—Written comments are invited for publication; the last discussion should be submitted by *December 1, 1952.*

[1] Chf. Research Hydrologist, Weather Bureau, U.S. Dept. of Commerce, Washington, D.C.

[2] "Applied Hydrology," by R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, McGraw-Hill Book Co., Inc., New York, N. Y., 1949, pp. 537-541.

[3] "Electronic Device Speeds Flood Routing," by R. K. Linsley, L. W. Foskett, and M. A. Kohler, *Engineering News-Record*, Vol. 141, 1948, pp. 64-66.

[4] "Engineering Construction—Flood Control," by G. T. McCarthy, The Engineer School, Ft. Belvoir, Va., 1940, pp. 147-156.

this equation, provided the resistances R_1 and R_3 are equal and the capacitance of condensers C_1 and C_2 are equivalent. In this case,

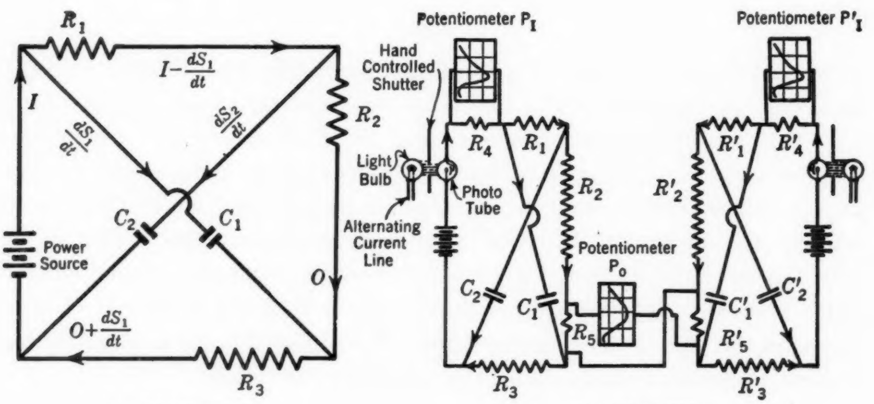
$$K = 2\,(R_1\ C_1 + R_2\,C_1) \qquad (2)$$

and

$$x = \frac{R_1}{2\,(R_1 + R_2)} \qquad (3)$$

Thus, by using fixed capacitance the circuit can be adjusted to any paired values of K and x if the proper values of resistance are set at three points in the circuit.

Circuits.—This is the basic circuit used in the flow analog. In practice, however, it is modified as shown in Fig. 1(*b*), to facilitate controlling the inflow current and observing both the inflow and outflow values. Moreover,



(*a*) SIMPLIFIED (*b*) COMPLETE

FIG. 1.—CIRCUIT DIAGRAM FOR ELECTRONIC FLOW ROUTING ANALOG

there are two identical circuits feeding to a common outflow potentiometer, making it possible to derive the outflow graph from two sources of inflow undergoing different storage characteristics. Actually, three, four, or more inflow sources can be treated in a similar manner by simply increasing the number of circuits. Self-balancing potentiometers are inserted in the circuit, across pick-up resistors, to record the inflow and outflow currents. The pick-up resistances are very small compared to the values of R_1, R_2, R_3 and, consequently, have no significant effect upon the characteristics of the circuit. To control the inflow current a photo-tube is inserted in the circuit and the light intensity activating this tube is regulated by a hand wheel.

Fig. 2 is a photograph of the analog as assembled. In operation, the plotted inflow graph is placed on the drum and the proper resistance values set on the panel. The inflow and outflow drums are synchronized and rotate at a constant speed. The lateral displacement of the pen representing the inflow discharge is controlled by the hand wheel, so the pen traces the plotted

hydrograph, thus maintaining the inflow current in the circuit in identical ratio with the discharge. Simultaneously, the pen on the center potentiometer records the routed outflow hydrograph.

PROCEDURE FOR ROUTING EFFECTIVE RAINFALL

Analytic Method.—The usual method of preparing flood forecasts for headwater areas involves: (1) The computation of runoff volume (effective rainfall) from a rainfall-runoff relation; and (2) the distribution of this volume through time by application of a unit hydrograph or distribution graph. The pre-

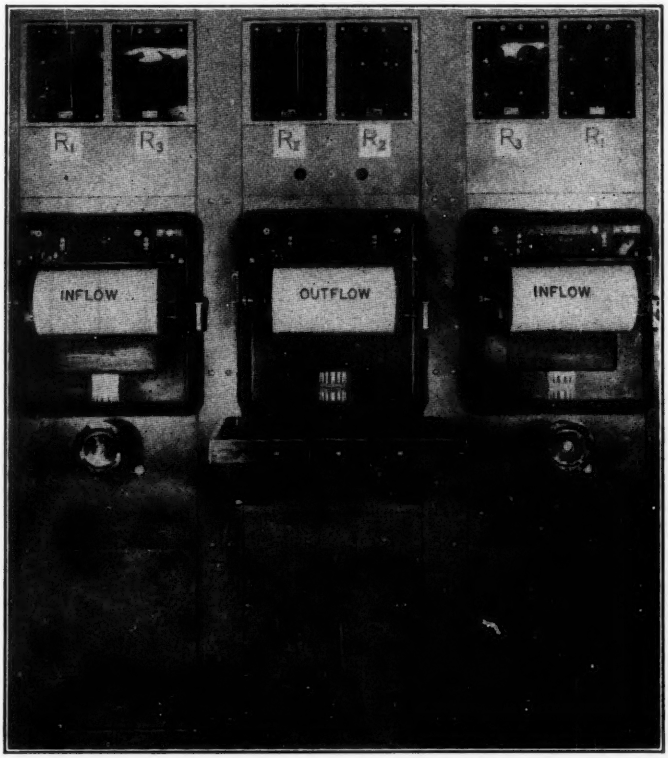


FIG. 2.—PHOTOGRAPH OF ELECTRONIC FLOW ROUTING ANALOG

dicted flow for a point downstream is then derived by routing the upstream flow and adding the estimated flow from the local (marginal) area between the two points. The hydrograph for a local area is derived in the same manner as that of a headwater basin, using a rainfall-runoff relation and distributing the derived runoff volume through time. By repeating the process, reach by reach and stream by stream, forecasts are prepared for an entire river basin. This approach is somewhat inflexible, since a forecast can be prepared for a particular point only after all upstream forecasts are available. Moreover,

keeping the reaches of optimum length frequently makes it necessary to predict the hydrograph for points at which the forecasts are of little or no value. By routing the effective rainfall, however, a priority system can be used, preparing first the forecasts for those areas in which the flood threat is the most serious.

Use of the Analog.—The concept of simulating the hydrograph at a point by routing effective rainfall over the area above the point is not new. It is essentially the approach described by C. O. Clark,[5] A. M. ASCE, and has been considered by numerous other hydrologists.[6,7] The assumed inflow hydrograph is derived by lagging effective rainfall over various sub-areas in pro-

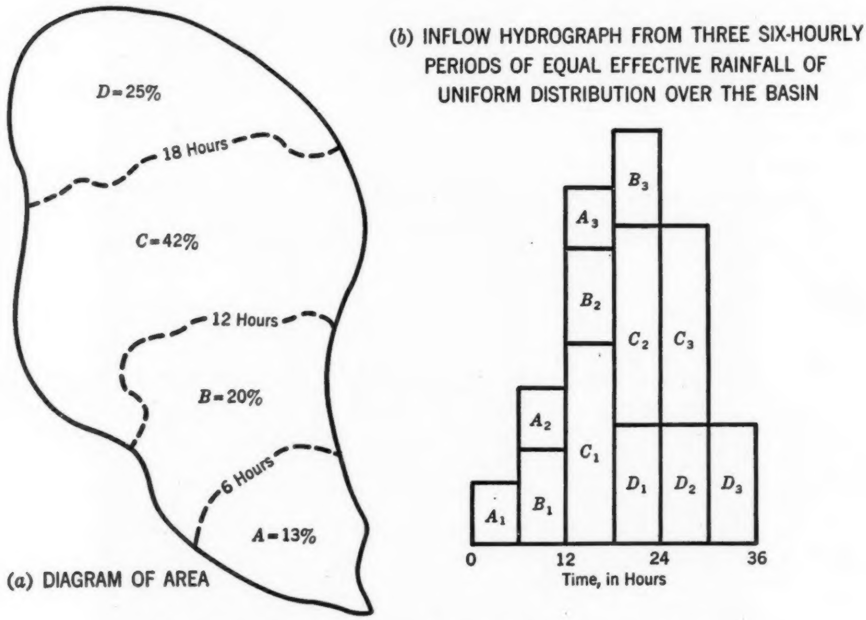


FIG. 3.—DERIVATION OF INFLOW GRAPH OF EFFECTIVE RAINFALL

portion to the travel time above the gaging station. Thus, in Fig. 3, the blocks A_1, B_1, C_1, and D_1 are in direct proportion to the areas of zones A, B, C, and D, respectively, and therefore constitute the inflow graph for one 6-hr period of effective rainfall, evenly distributed over the basin. Similarly, elements labeled with subscripts 2 and 3 are the result of rainfall occurring in the second and third 6-hr periods, respectively. The total inflow graph of storm runoff is thus derived by taking 6-hourly increments of effective rainfall over the

[5] "Storage and the Unit Hydrograph," by C. O. Clark, *Transactions*, ASCE, Vol. 110, 1945, pp. 1419–1488.

[6] "Virtual Channel-Inflow Graphs," by R. E. Horton, *Transactions*, Am. Geophysical Union, 1941, pp. 811–819.

[7] "The Flood Hydrograph," by H. M. Turner and A. J. Burdoin, *Journal*, Boston Soc. of Civ Engrs., Vol. XXVIII, July, 1941, p. 232.

various zones, converting to mean cubic feet per second, and lagging to the outflow point.

Inflow graphs of effective rainfall can be converted to simulated outflow hydrographs by one of a number of routing techniques. Since storage is appreciably influenced by inflow, results are generally not satisfactory if storage is assumed to be a function of outflow only. Since the flow analog assumes storage to be a function of both inflow and outflow, it provides an efficient means of routing effective rainfall.

Determination of Factors.—Having derived inflow hydrographs for a number of past storms, the next step in the development of the procedure is the determination of the most suitable values of K and x (in Eq. 1) for the basin. In all routing with the analog, it has been found that proper values of K and x can be derived more rapidly by trial-and-error routing than by the method originally presented by G. T. McCarthy.[4] The coefficient K is expressed in units of time and is approximately equal to the time of travel, while the factor x defines the relative effect of inflow and outflow in determining storage. Assuming K equal to the average lag between inflow and outflow peaks and assigning x an arbitrary value of about 0.2 (found to be a good average value), each inflow graph is routed and compared with observed outflow, less base flow. If examination reveals a consistent variation between computed and observed hydrographs, the required changes in K and x are estimated from a standard chart that displays the effects of such variations on the routed hydrograph. Two or three runs of the several hydrographs will usually provide suitable values of K and x.

Logically, it would seem that the value of K should be larger when the storm is centered in the headwaters than when most of the flow originates near the gaging station. Analyses indicate the areal distribution can vary considerably without seriously affecting the results obtained from average values of K and x. Generally speaking, however, results can be improved by using a relatively large value of K for upstream floods, and vice versa. This effect can be reduced by dividing the upstream portion into relatively more time zones than flow velocities would indicate, thus effectively flattening the upstream inflow. Since the flow analog in use can accommodate inflow from two sources, the most efficient approach is a division of the inflow into two parts. In this manner, the upstream and downstream flows can be routed with different storage factors and, if necessary, the analog can be expanded to provide for three or more sources of inflow.

Potomac River Study.—A rather thorough analysis has been made for the Potomac River Basin in which average values of K and x were determined for six sub-basins having a drainage area ranging from 1,470 to more than 11,000 sq miles. Fig. 4 shows typical results for the lowermost gaging station on the Potomac. The inflow graphs to be routed were constructed by connecting the mid-points of the 6-hourly mean flows. The values of K and x used in these cases are the best over-all values derived for a series of storms. The April, 1937, flood was definitely an upstream flood and the agreement between routed and observed flows is improved by using divided inflows, as demonstrated in Fig. 5. This figure shows the comparative results for Point of Rocks, Md., the first gaging point above the Washington station.

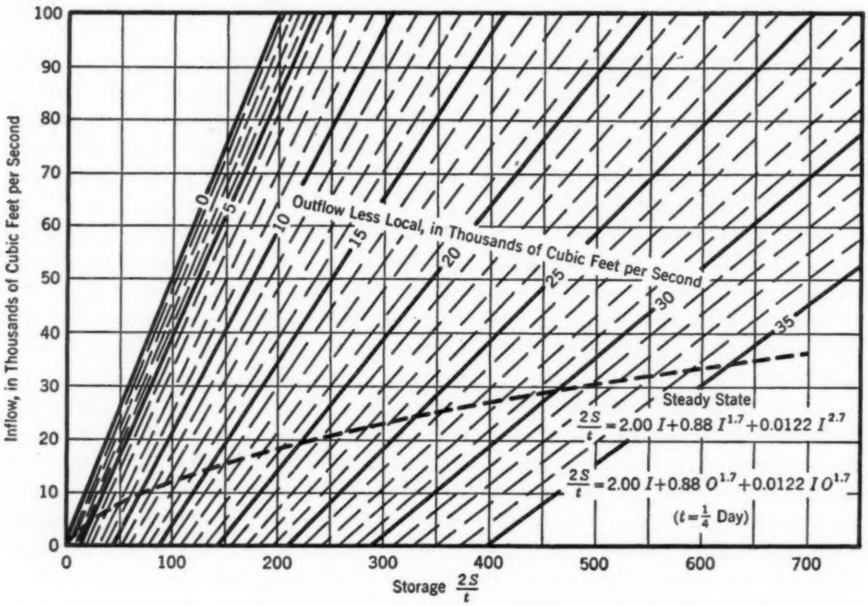


FIG. 4.—ROUTED AND OBSERVED HYDROGRAPHS FOR THE POTOMAC RIVER NEAR WASHINGTON, D. C.

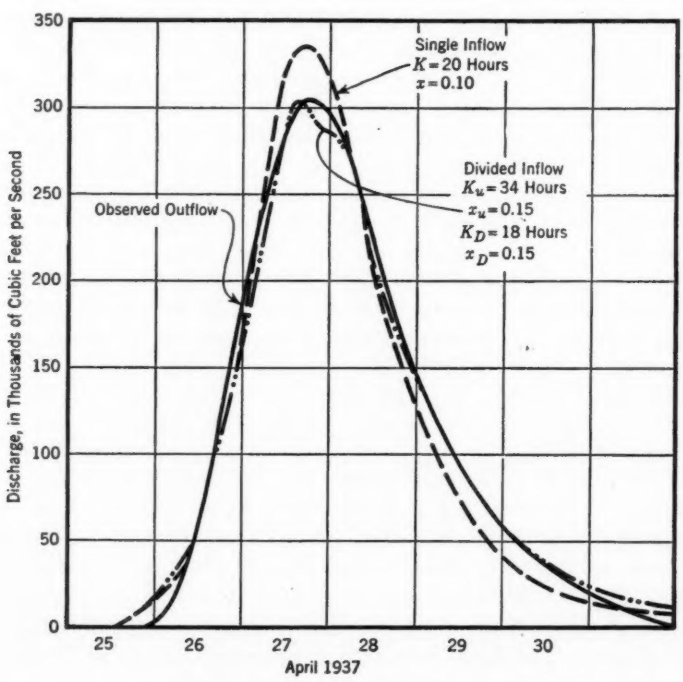


FIG. 5.—COMPARATIVE RESULTS USING SINGLE AND DIVIDED INFLOW (EFFECTIVE PRECIPITATION)

Applicability of Muskingum Equation

Limitations of the Analog.—The electronic flow analog has a decided advantage over analytical and graphical methods in that it solves the storage equation in differential rather than incremental form. In addition, the entire hydrograph can be routed more rapidly than by conventional techniques. The analog in use has chart speeds of 1 and 2 in. per min, while later models will run at 2 or 4 in. per min. Nevertheless, the analog is still somewhat inflexible, since its applicability is limited to the Muskingum storage function, which assumes storage proportional to flow.

In applying the flow analog to channel reaches and basins in the east and middle west, cases have been encountered in which the Muskingum equation is not applicable. It is known that the discrepancies result in part from the necessity of utilizing excessively long reaches, a deficiency that could be overcome by successive routing through short, arbitrary sub-reaches. That is, the inflow could be routed with half the value of K required for the reach, and the resulting flow routed again to obtain the outflow hydrograph. This approach would, however, greatly increase the time required to prepare forecasts.

Cumberland River Study.—Those cases in which the analog did not yield satisfactory reproduction of the outflow hydrograph were analyzed to determine the storage function, with the expectation that another circuit might be designed which would be sufficiently generalized to embrace these exceptions. Storage data were computed from inflow and outflow hydrographs and plotted to derive relations similar to that shown in Fig. 6(a). Although the plotted data in some cases indicate that a rather complex, curvilinear relation exists, the function does not appear to be of the generally accepted form:

$$S = K\left[x\,I^m + (1 - x)\,O^m\right] \qquad (4)$$

in which the exponent, m, is assumed to be positive and constant for a particular reach.

In the case of the Cumberland River from Wolf Creek Dam (Kentucky) to Celina (Tenn.), a family of curves was first constructed to fit the data best and a number of inflow graphs routed. Then the data were fitted to a relatively simple function of the form:

$$S = a\,I + b\,O + c\,I\,O \qquad (5)$$

in which a, b, and c are constants as shown in Fig. 6(b). The inflow graphs were then routed again.

This function was tested because it seemed plausible that an electrical circuit could be designed for the function and because the plotted data indicated it was the simplest equation that could be expected to yield satisfactory duplication of the outflow hydrograph. An examination of the equation will reveal the fact that it is identical with the Muskingum equation, except for the added term involving the product of inflow and outflow. This term, however, introduces curvature in the storage-flow relation. That is,

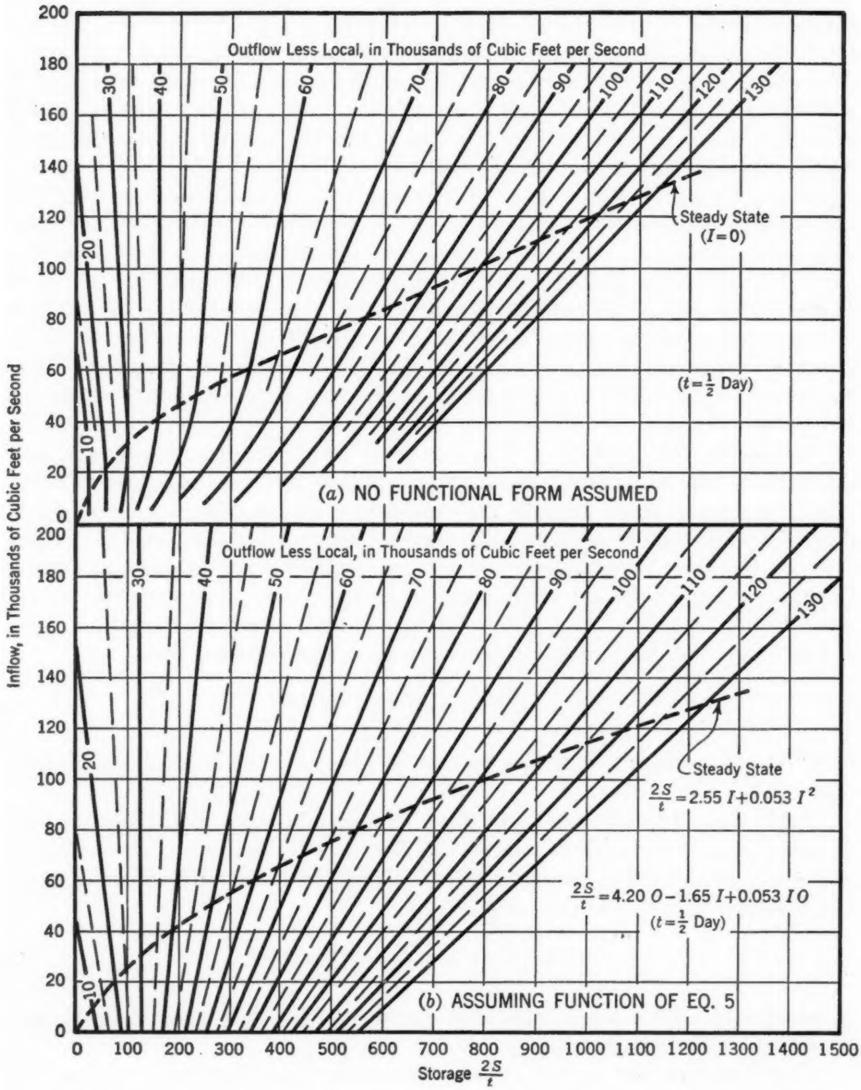


FIG. 6.—STORAGE RELATIONS FOR CUMBERLAND RIVER, FROM WOLF CREEK DAM, KENTUCKY TO CELINA, TENN.

for steady-flow conditions ($\dot{I} = 0$), Eq. 5 becomes

$$S = g\,I + c\,I^2 = g\,O + c\,O^2 \quad \text{.................. (6)}$$

in which $g = a + b$. The curve is also shown in Fig. 6(*b*).

For the Cumberland reach, Eq. 5 was found quite satisfactory, as is shown in Fig. 7. The routing curves were based on ten rises, and agreement in the other eight rises is comparable to that for the two cases shown. Some of the apparent discrepancies between routed and observed outflows undoubtedly result from errors in estimated distribution of local flow. The results of routing with Eq. 5 were considered satisfactory for all reaches analyzed. It was revealed, however, that there is often a significant loss in accuracy in using Eq. 5 as compared to a more complex function determined by fitting a family of curves to plotted storage and flow data (Fig. 6(*a*)).

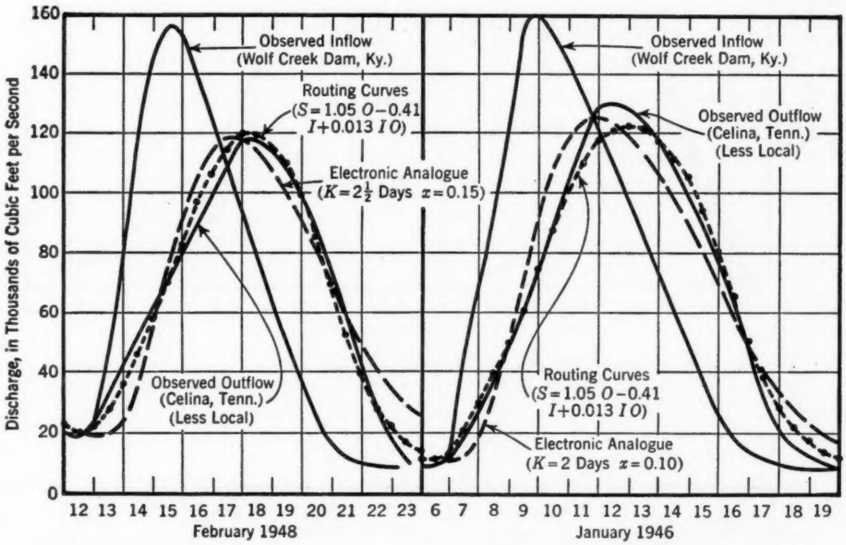


FIG. 7.—ROUTED AND OBSERVED HYDROGRAPHS FOR CUMBERLAND RIVER, WOLF CREEK DAM, KENTUCKY, TO CELINA, TENN.

Verdigris River Study.—A comparison of results between Eq. 5 and the flow analog for a reach of the Verdigris River between Independence, Kans., and Lenapah, Okla., is shown in Fig. 8. The steep recession characteristic of this stream cannot be duplicated by routing from station to station with the analog.

General Storage Equation.—As previously stated, Eq. 4 is generally accepted as the true form of the storage equation. In those cases studied for which the analog was not satisfactory, however, this equation did not appear to be materially better. The equation that appears to be most generally applicable (Fig. 9) is of the form:

$$S = a\,I + b\,O^n + c\,I\,O^n \quad \text{.................... (7)}$$

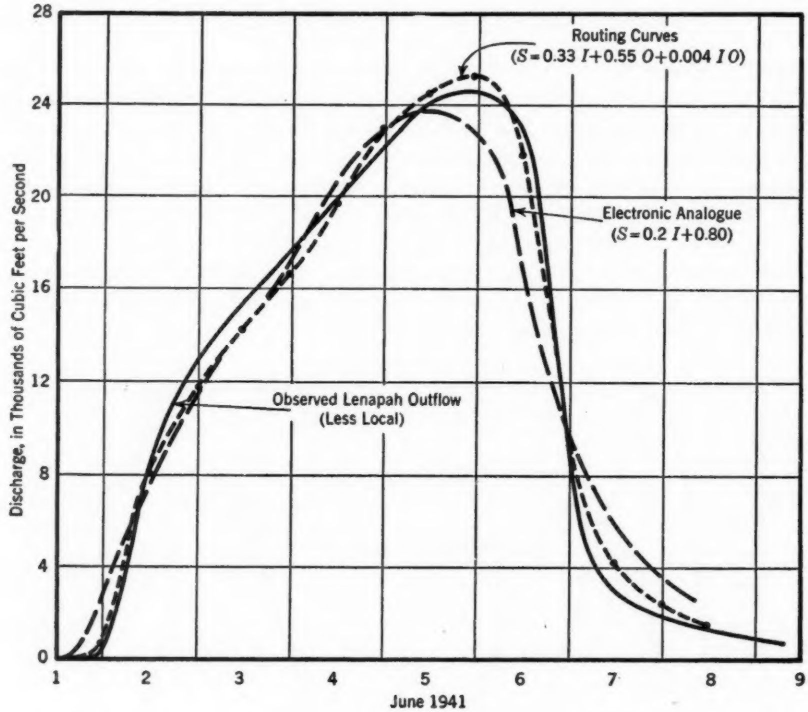


FIG. 8.—ROUTED AND OBSERVED HYDROGRAPHS FOR VERDIGRIS RIVER, FROM INDEPENDENCE, KANS., TO LENAPAH, OKLA.

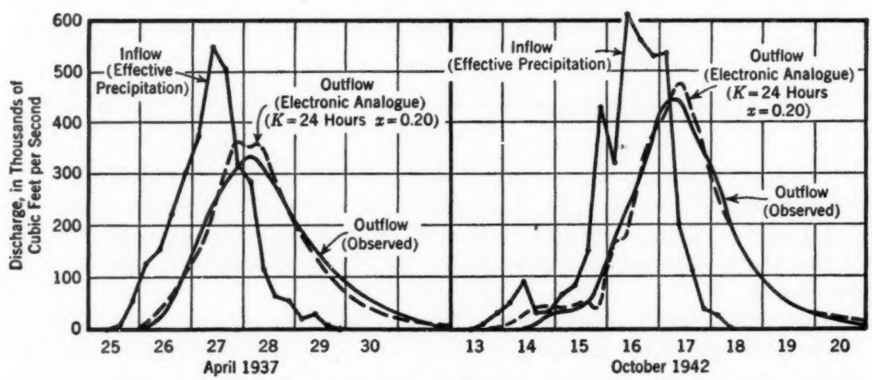


FIG. 9.—STORAGE FUNCTION FOR VERDIGRIS RIVER ABOVE INDEPENDENCE, KANS.

Although the theoretical aspects of this function have not been investigated, it will be noted that when $n = 1$, Eq. 7 reduces to the form of Eq. 5, and if the added qualification is made that c equals zero, it takes the form of the Muskingum equation. In at least one instance, the plotted data indicated an exponent on the inflow term also. This would make Eq. 7 identical with Eq. 4 except for the product term. It is believed that this term results from the fact that instantaneous values of inflow and outflow do not completely determine storage because of variations in the water surface profile. In this event, its importance should diminish as shorter reaches are considered.

Conclusions

Results of analyses have proved the flow analog to be an efficient tool for the preparation of river forecasts. It is equally adaptable to the routing of flow from point to point along the stream or to the direct routing of effective rainfall. The Weather Bureau is engaged in a program in which flow analogs will be placed in all its river forecast centers.

The Muskingum storage equation, and, therefore, the analog circuit now being utilized, yields satisfactory results in a large percentage of cases. There are, on the other hand, instances in which a more complex storage function is required for the satisfactory synthesis of the outflow hydrograph. On the basis of current studies, it appears that a three-term storage equation of inflow, outflow, and their product would be satisfactory in virtually all cases. Attempts are now being made to design a corresponding circuit and thus enhance the utility of the flow analog.

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